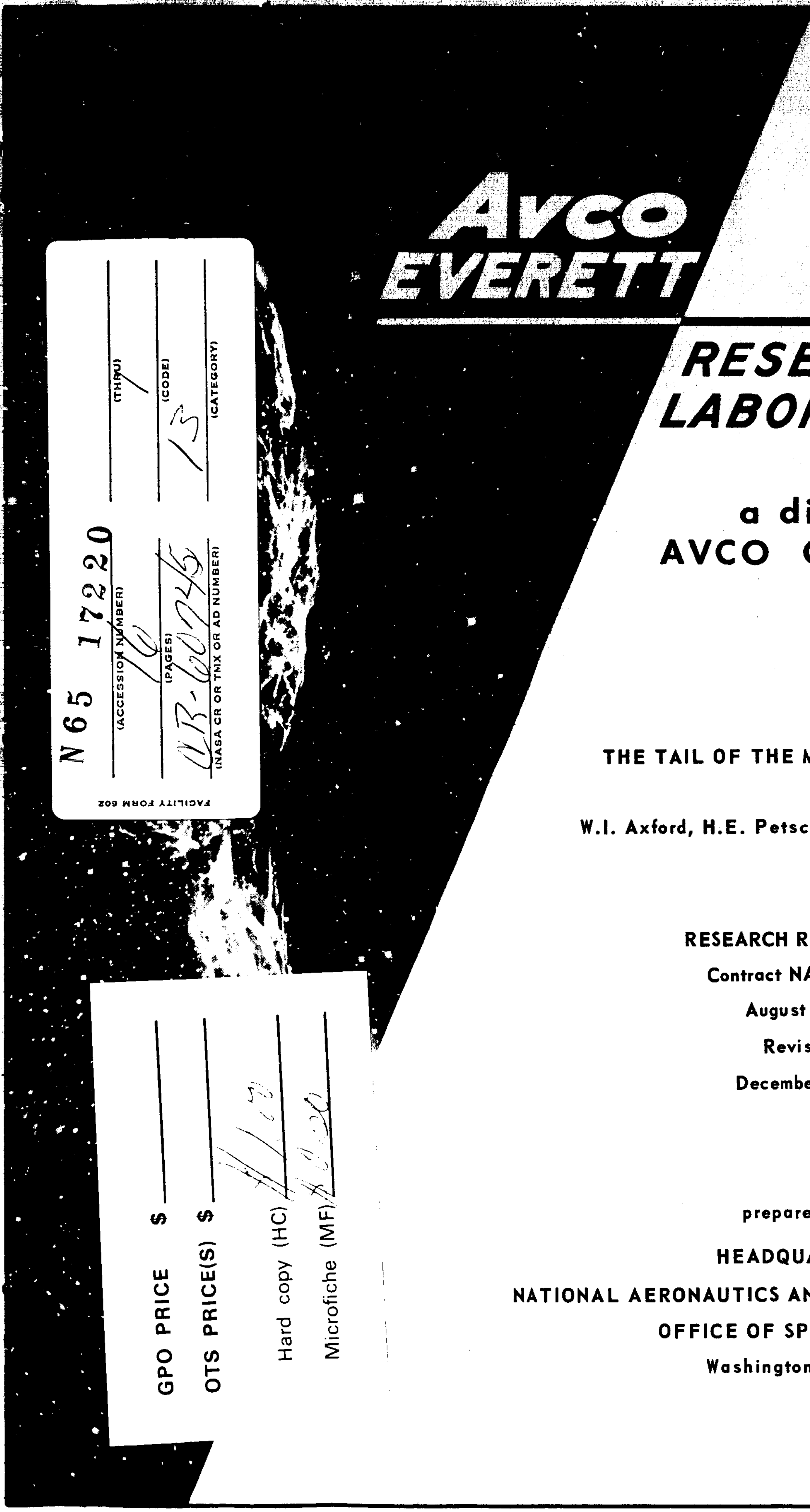

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THE TAIL OF THE MAGNETOSPHERE

W.I. Axford, H.E. Petschek, and G.L. Siscoe

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THE TAIL OF THE MAGNETOSPHERE

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The Chapman and Ferraro (e.g. Beard, 1960) model of the magnetosphere is entirely dissipationless, and as a consequence contains no tangential stress at the magnetosphere boundary. It has been suggested that either viscous interaction (Axford and Hines, 1961; Piddington, 1963) or reconnection of field lines (Dungey, 1961; Levy, Petschek and Siscoe, 1963) can give rise to tangential stresses which produce internal convection within the magnetosphere. A number of auroral and ionospheric observations appear to be consistent with such a convection pattern. It was also suggested (Piddington, 1960) that tangential stresses might stretch the magnetosphere tail and thus account for the main phase of magnetic storms. In the present paper we wish to observe that recent measurements related to the magnetosphere tail lend further support to the suggestion that tangential stresses play a significant role. In particular the observations of a strong magnetic field in the tail aligned radially from the earth, the departures of the magnetic field from the Finch and Leaton field in the neighborhood of 5-12 earth radii in the anti-solar direction, the existence of particle fluxes in the tail, the latitude of the boundary of trapped particles as well as its day-night asymmetry and the low energy cosmic ray cutoff are all consistent with this picture. Furthermore it appears that the tail provides a specific mechanism for injection of energy into the body of the magnetosphere.

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In the solar direction the normal stresses predominate and the magnetosphere shape in this region is therefore determined with reasonable accuracy by the standard calculations. However, in the tail tangential stresses can stretch out the field lines and thus the field configuration tends towards the configuration illustrated in Fig. 1, i. e. field lines directed more or less radially with respect to the earth. Since the lines from the north and south poles are in opposite directions, there must be an essentially neutral plane across which the field direction changes from radially outward to radially inward. The orientation of this plane is probably determined primarily by the direction of the solar wind and the orientation of the dipole axis of the earth. Thus roughly, the plane should contain the sun-earth line and the line perpendicular to this and the dipole axis. Some departures from this orientation which depend upon the direction of the interplanetary magnetic field may also exist particularly if field reconnection is the predominant source of tangential stress. The plane will also wobble about the sun-earth line as the earth rotates.

The magnitude of the field in the tail as measured by Explorer X (Heppner et al, 1963) and Explorer XIV (Cahill, 1964) varies from about 30 to 50 γ at 15 earth radii to 15 to 20 γ near 40 earth radii. This magnitude is consistent with earlier estimates of the strength of the internal convection pattern and the estimated rate at which field lines move towards a neutral plane. In the convection pattern the polar field lines are pulled back by the solar wind and therefore move across the poles in an anti-solar direction. For a steady flow pattern the total rate at which field lines cross the neutral plane in the tail and then return to the day side of the magnetosphere must equal the rate at which they cross the polar cap. This is equivalent to saying that the electric potential across the polar cap due to the tailward motion of the field lines in the ionosphere must be equal to the electric potential associated with annihilating field lines at a neutral line, which, in turn, is equal to the amount of magnetic flux annihilated per unit time. This can be seen by expressing the rate of annihilation of flux in the form $Bv_B L$ where v_B, the velocity at which the field lines are sucked into the neutral line, is the local $\frac{E}{B}$ velocity and L is the effective length of the neutral line which should be approximately the breadth of the tail. The electric potential across the polar cap (i. e. $v \times B \ell$ for the polar cap) has been previously estimated as $\phi = 30$ KV, (Levy, Petschek and Siscoe, 1963). The analysis of the flow in the neighborhood of a neutral sheet (Petschek, 1964) predicts the drift velocity of field lines towards a neutral sheet of approximately one-tenth of the Alfven speed outside the sheet. Thus in the tail

$$\frac{cE}{B} = \frac{.1 B}{\sqrt{4 \pi \rho}} = \frac{c\phi}{LB} \tag{1}$$

Taking the breadth of the tail $L = 2 \times 10^5$ km and choosing a density of $1/cm^3$, the above equation gives a magnetic field in the tail of $B \approx 10\ \gamma$ which is consistent with but somewhat smaller than the measured values. The somewhat arbitrary choice of density above was based on the assumption that the ambient plasma enters the tail region from outside. It should then have a density less than the density of about $20/cm^3$ in the transition region. The estimated value of B depends only on the fourth root of the density, thus a particle density of $10/cm^3$ would correspond to a magnetic field of about 15 γ.

The current system associated with the neutral sheet is shown in Fig. 2, which is a cross section through the meridian plane containing the sun-earth line, and in Fig. 3, which is a cross section through the magnetospheric tail as seen from the earth. Also indicated in Fig. 2 is a Chapman-Ferraro type current system projected onto the meridian plane. The total field in the magnetosphere can be considered as the sum of four fields: the dipole field of the earth, $\vec{H}_E$, the field associated with the Chapman-Ferraro surface current, $\vec{H}_{CF}$, the ring current field, $\vec{H}_R$, and $\vec{H}_T$, the field associated with the currents in the tail. The field configurations for $\vec{H}_{CF}$ and $\vec{H}_T$ are sketched in Fig. 4; they have exactly opposite behavior in two significant respects. The $\vec{H}_{CF}$ field is concave toward the sun and adds to $\vec{H}_E$ in the vicinity of the equator, whereas, $\vec{H}_T$ is the convex toward the sun and, like $\vec{H}_R$, opposes $\vec{H}_E$ in the vicinity of the equator.

The shape and strength of the "disturbance" field ($\vec{H}_{measured} - \vec{H}_E$) as observed from Explorer VI and Explorer X (Smith, 1962) is superimposed on Fig. 4. The superposition is made by rotating the meridian plane containing the satellite to coincide with the noon-midnight meridian plane. Thus, Fig. 4 does not indicate the actual trajectory of the satellites, since their orbits did not lie in a particular meridian plane, and, in fact, the last measurement shown for Explorer X is at about the position where it intersected the magnetosphere boundary. A further qualification to note is that the Explorer VI data refers to a magnetically disturbed period. However, even with these qualifications, the data indicates a disturbance field that is convex toward the sun and which tends to depress the field near the earth at the equator. The magnetic measurements made from Explorer XIV confirm this general behavior (Cahill, 1964); the field changed from an essentially dipole field within 8 to 10 earth radii to an essentially radial field of 30 to 50 γ pointing away from the earth and sun beyond about 12 earth radii. The field was also depressed relative to the Finch and Leaton field by as much as 20 γ at distances less than 8 earth radii. The apparent depression of the field could be due partly to the effect of the neutral sheet and not entirely to a ring current. As can be seen from Fig. 4, the magnitude of $\vec{H}_T$ in the equatorial region falls off slowly with distance away from the neutral sheet, so that its strength at the earth is roughly the same as it is in the tail. Thus if the tail field can rise to 100 γ during a magnetic storm, $\vec{H}_T$ might contribute substantially to the main phase (Piddington, 1960). However, $\vec{H}_T$ can not provide the entire explanation of the main phase since $\vec{H}_{CF}$ is of the opposite sign and necessarily larger than $\vec{H}_T$ for a steady flow configuration, and unsteady effects are probably not important since the duration of the main phase is much larger than the time required for the solar wind to go a distance comparable with the magnetosphere diameter.

Since the magnetic field strength becomes very small in the neutral sheet, the presence of plasma is required to maintain pressure equilibrium. This region of hot plasma expands at an angle of about one tenth of a radian (Petschek, 1964) from the neutral line (Fig. 1). If the neutral line is located a few tens of earth radii in the tail, then the thickness of the sheet should be of the order of a few earth radii. The particle density within the neutral sheet should be about twice that outside of the sheet and the energy density can be determined from the condition $p + B^2/8\pi$ = constant across the sheet. Choosing a particle density of $2/cm^3$ consistent with our earlier estimate and a field of 30 γ outside the sheet gives an average particle energy of 1 keV and an electron flux of $3 \times 10^8/cm^2$ sec ster. Low energy electron detectors on Lunik (Gringauz, et al, 1960) and Explorer XII (Freeman, 1964) have indicated the existence of regions of high electron flux on the night side near the magnetic equator. Quantitatively the results are however somewhat ambiguous. Gringauz, et al (1961) quote fluxes of about $2 \times 10^7/\mathrm{cm}^2$ sec ster of electrons with energy > 200 eV, while Freeman (1964), using a total energy detector which is sensitive between .5 and 40 kv finds fluxes of $2 \times 10^{10}/\mathrm{cm}^2$ sec ster if one assumes electron energies of 1 keV. The neutral sheet analysis (Petschek, 1964) requires shock waves bounding the neutral sheet. These waves presumably involve a turbulent dissipation process. Thus one may also expect a non-thermal high energy particle distribution. Increased fluxes of electrons above 40 keV have been observed in the expected neighborhood of the neutral sheet (Frank, et al, 1963, 1964 and Singer, et al, 1964).

Due to the sharp curvature of the field lines going through the neutral sheet the plasma within the sheet will be pulled towards the earth at a velocity corresponding to the Alfven speed outside the sheet (Petschek, 1964). This plasma flow then represents a flux of energy into the magnetosphere. Since this plasma already contains field lines, both of whose ends connect to the ionosphere, this flow can penetrate to low L values more readily than, for example, the direct solar wind. The magnitude of this energy flux is the product of the energy density, the flow velocity and the area of the neutral sheet in the plane illustrated in Fig. 3. Taking into account the number of degrees of freedom and the directed flow energy, the energy density is three times the pressure or $3\ B^2/8\pi$ outside of the sheet. Thus

$$\phi = \frac{3B^2}{8\pi} \frac{B}{\sqrt{4\pi\rho}} LW \approx 4 \times 10^{17}\ W\ \mathrm{erg/sec} \tag{2}$$

where consistent with earlier numbers we have taken $B = 10\ \gamma$, a particle density of $1/cm^3$ and the breadth of the tail $L = 2 \times 10^{10}$ cm. The width of the neutral sheet (vertical dimension in Figs. 1-3) W is to be measured in units of earth radii in the last expression, and is therefore very roughly of order unity. Several authors have estimated the energy required to account for auroras and electron precipitation from the magnetosphere. For example, Axford (1964) and O'Brien (1964) obtain 10^{17} and 4×10^{17} erg/sec respectively. Thus the energy input provided by the flow in the neutral sheet appears to be sufficient to account for these phenomena. The rate of energy input required to build up the ring current for the main phase of a magnetic storm has been estimated by several authors. For example, Axford (1964) obtains 2×10^{18} erg/sec. Since ϕ is very sensitive to the magnetic field ($\sim B^3$), it seems likely that during a storm it can increase by an order of magnitude above the numerical estimate in equation 2. The rough agreement of these estimated and required energy fluxes suggests that the flow in the neutral sheet may provide the specific mechanism by which some of the energy extracted from the solar wind by tangential stresses at the boundary is injected into the body of the magnetosphere.

The field lines on either side of the neutral sheet in the tail come from regions around the poles of the earth. The latitudinal extent on the surface of the earth of these regions can be estimated from the measured field strengths in the tail and the approximate cross sectional area of the tail. Observations suggest that the field strength in the tail at a radial distance of 15 earth radii is typically 30 γ and the radius is of the order of 20 earth radii. Hence, the amount of magnetic flux that penetrates the upper half of a cross section though the tail at this distance is roughly 7.10^{16} maxwells. The field lines associated with this flux enter the earth in a region around the north magnetic pole within an area corresponding to a circle with colatitude, λ_c, of roughly 18°. This estimate is conservative, since it neglects any penetration of fields through the boundary. λ_c should mark the high latitude boundary of trapping on the noon geomagnetic meridian, and we note the range of values quoted for λ_c is consistent with the observations made by the Alouette satellite, (McDiarmid and Burrows, 1964) which indicate a colatitude of the trapping boundary of 18° on the day side and 25° on the night side.

The observation that the boundary of trapping on the night side of the earth occurs at a lower geomagnetic latitude than on the day side also appears to be qualitatively consistent with the picture described above. Previous calculations based on conservation of the second adiabatic invariant and a Chapman-Ferraro type field configuration do not give a sufficient day-night asymmetry (Hones, 1963). The stretching of the field lines associated with the possible neutral sheet would tend to increase the calculated asymmetry.

It seems possible that the high latitude boundary of the trapped particles also marks the termination of the low energy cosmic ray cutoff (Fan, et al, 1964), since these particles are likely to have little difficulty drifting across the breadth of the tail; however, some scattering in pitch angle may be necessary to account for the relatively uniform precipitation that seems to occur above the cutoff. Also if geomagnetic field lines penetrate the boundary, cosmic rays can travel along them directly to the polar regions.

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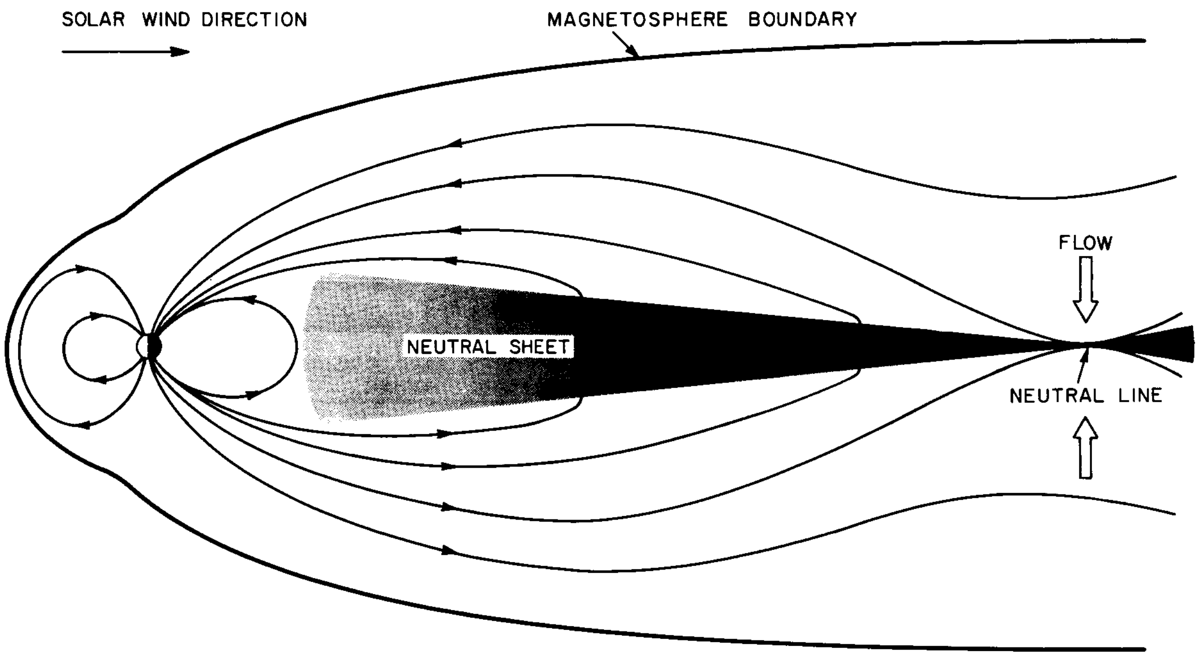

Fig. 1 Sketch of the magentic field configuration in the noon-midnight meridian plane, showing the effect of dragging field lines into the tail by means of tangential stresses at the boundary. The anti-solar neutral line which is perpendicular to the plane is indicated as well as the approximate location of the neutral sheet. The shading in the neutral sheet is meant to indicate the possible existence of a low energy electron flux.

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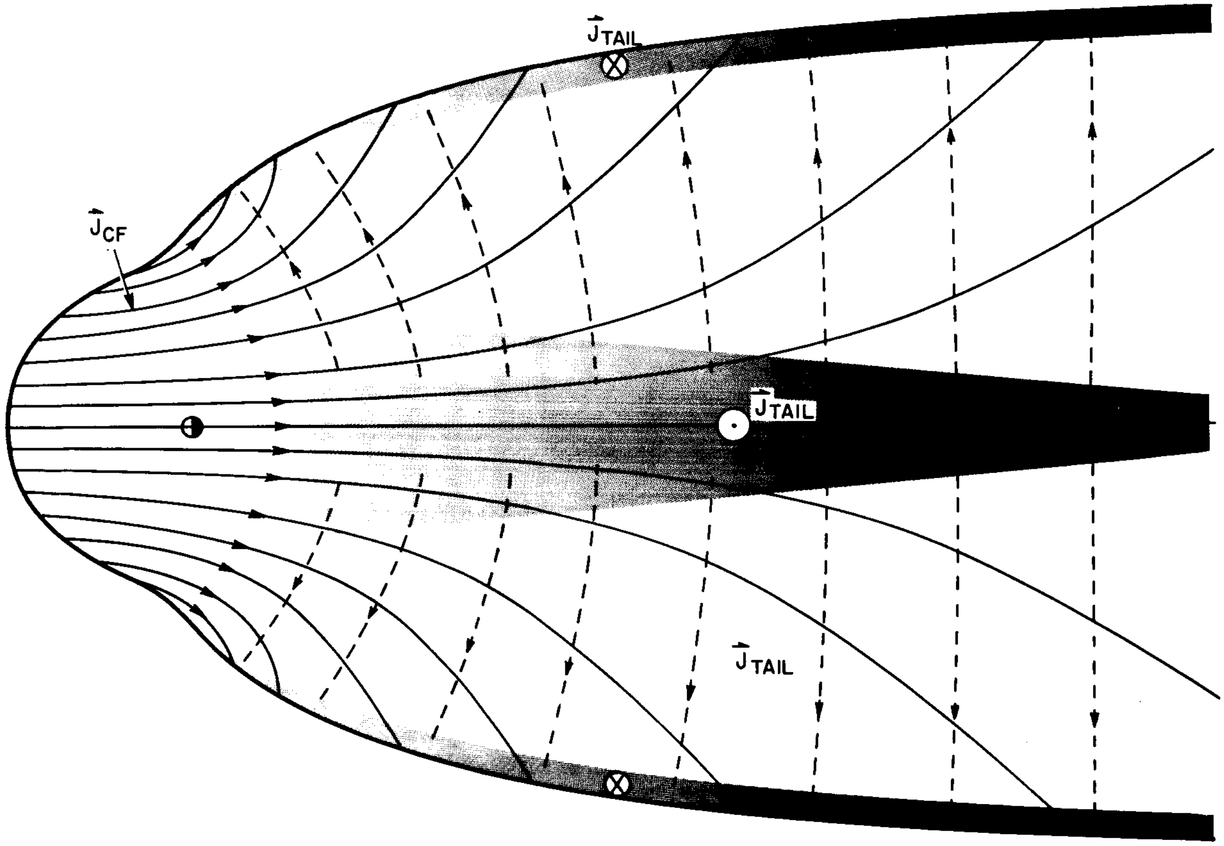

Fig. 2 A projection onto the noon-midnight meridian plane of the Chapman-Ferraro current system, $\vec{J}_{CF}$, and the tail current system, $\vec{J}_{TAIL}$. The Chapman-Ferraro current system flows entirely on the magnetosphere boundary. The tail-current system flows into the plane of the paper on both the top and bottom surfaces and returns in the neutral sheet.

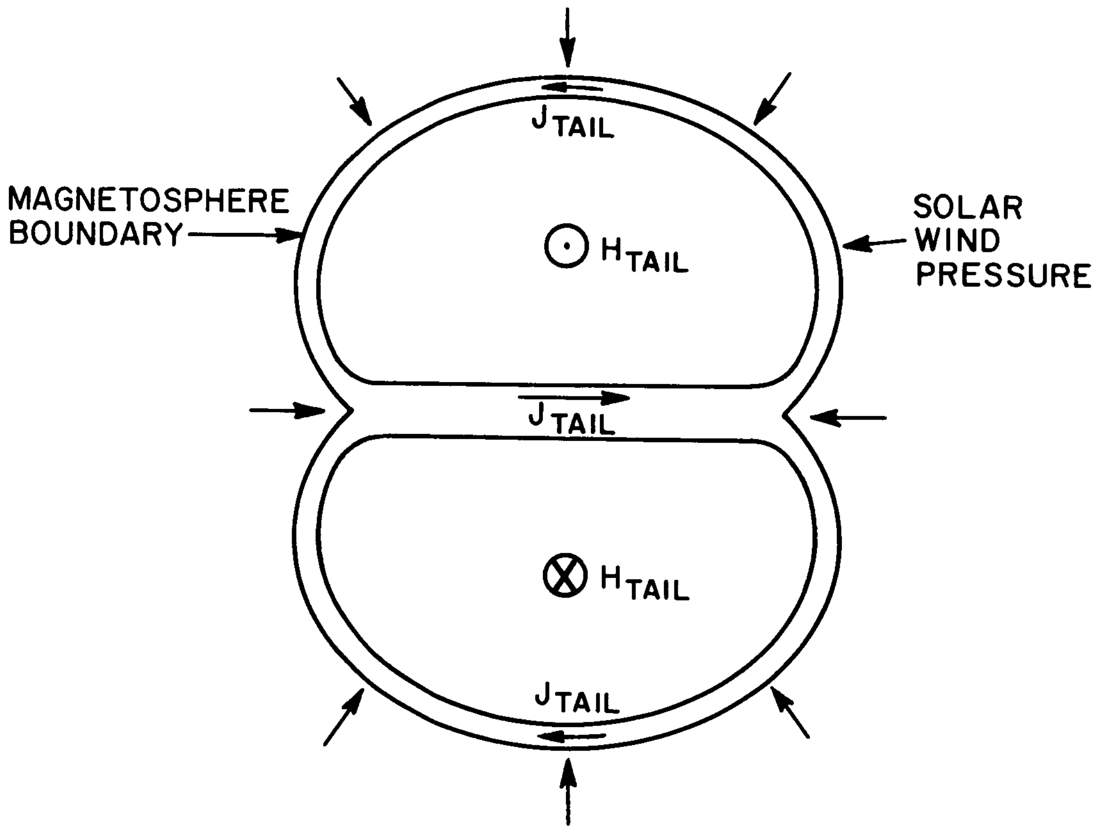

Fig. 3 A cross section through the magnetosphere tail is seen from the earth, showing the topology of the tail current system.

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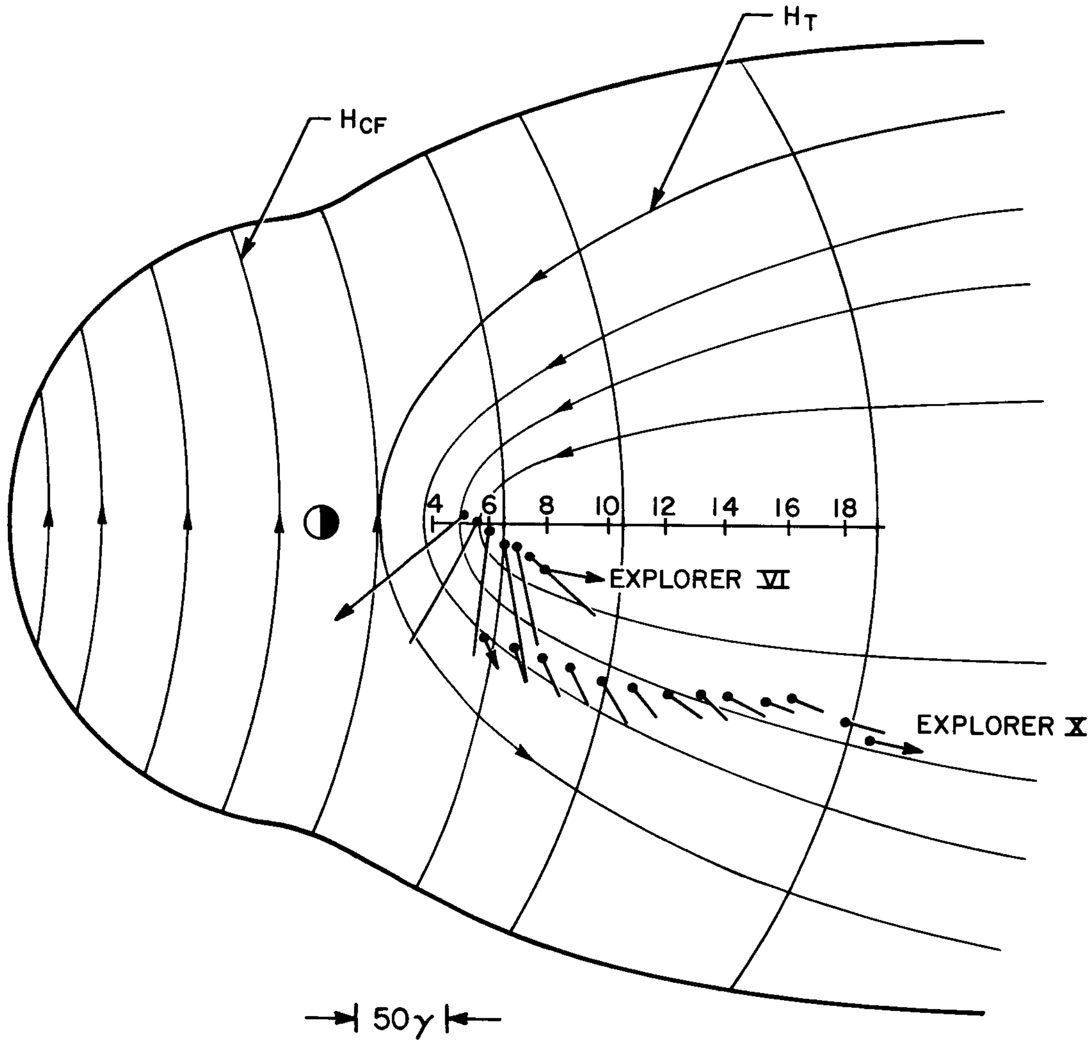

Fig. 4 A sketch of the magnetic field topology associated with the Chapman-Ferraro current system, H_{CF}, and the tail current system, H_T. Also shown is the distortion field ($\vec{H}_{measured} - \vec{H}_E$) measured by Explorer VI and Explorer X, (Smith, 1962) which is seen to have the qualitative features of H_T.

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